AD-A114 075 NAVAL COASTAL SYSTEMS CENTER PANAMA CITY FL F/G 6/17
THE DEVELOPMENT OF AN IMPROVED SUIT SYSTEM FOR COLD WATER DIVIN--ETC(U)
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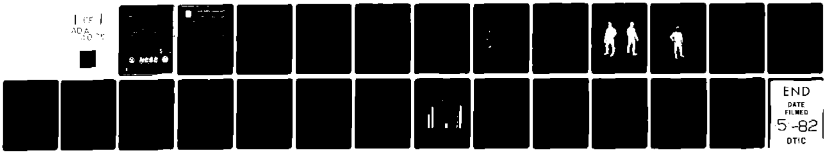

TECHNICAL
MEMORANDUM
NCSC TM 336-82

FEBRUARY 1982

THE DEVELOPMENT OF AN IMPROVED SUIT SYSTEM FOR COLD WATER DIVING

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ADMINISTRATIVE INFORMATION

The development effort summarized in this technical memorandum was performed during fiscal years 1977-1981 as part of the Navy's Diver Thermal Protection (DTP) project sponsored by NAVSEA 05R2. This phase of the DTP project is intended to provide improved thermal protection for shallow water operations when the breathing gas medium is air.

The authors wish to acknowledge the assistance of the Naval Clothing and Textile Research Facility during this development effort.

Released by
J. W. Grimes, Head
Life Support Systems Division
February 1982

Under authority of
W. T. Odum, Head
Diving and Salvage
Department

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER NCSC TM 336-82	2. GOVT ACCESSION NO. AD-A114 075	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Development of an Improved Suit System for Cold Water Diving		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Maxwell W. Lippitt Marshall L. Nuckols		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Coastal Systems Center Panama City, FL 32407		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE February 1982 13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Diving Suits; Swimmer Diver; Thermal Protection; Cold Water Diving; Thermal Undergarments

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The requirements for improved thermal protection garments for divers and a design philosophy for their development is discussed. An improved passive thermal protection garment for Navy divers has been shown to be thermally adequate in 4.4°C (40°F) water. Design investigations and thermal evaluations leading up to the final suit configuration are summarized.

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INTRODUCTION

Inadequate protection from cold water severely limits the ability of commercial or military divers to accomplish their missions. This problem has become more evident as advances in life support systems extend dive durations far beyond the capabilities of open-circuit scuba to the point where dives of more than 6 hours can now be accomplished.

The Naval Coastal Systems Center (NCSC) has undertaken the development of diver's thermal protection (DTP) equipment intended to meet the requirements of all Navy and Marine Corps diver/swimmer applications. Mission requirements of up to 6 hours duration in 35°F (1.7°C) water temperatures were identified as threshold criteria for the design of these thermal protection systems. [A goal of safe operations in 29°F (-1.7°C) water was established.] Maximum commonality for this equipment was sought to minimize the equipment inventory to meet the varied requirements of the combat swimmer, surface tended diver, or saturation diver.

Due to the extreme difference in thermal protection required for divers using air and heliox mixtures, a two-part program was established from the outset to satisfy these two needs.

1. Supplemental heating systems will be necessary for the diver using heliox mixtures to meet his thermal protection needs. The development of such systems is underway at NCSC.

2. On the other hand, a passively insulated garment having an inherent insulation of 1.0 to 1.5 clo* was found to be sufficient when air or oxygen/nitrogen breathing gas mixtures are used. The relative simplicity of passively insulated gaments, compared to active heating systems, makes their use desirable whenever conditons permit.

---

*clo - The amount of insulation required to maintain the average resting man in thermal equilibrium in a comfortable 70°F environment. A typical 1/4-inch foam neoprene wet suit offers approximately 0.75 clo at the surface. It will reduce to approximately 0.25 clo at 100 feet due to suit compression. One clo is defined as a quantity of thermal insulation whose thermal conductance is equal to 0.18M^2-hr-°C/Kcal.

The means of achieving this level of passive insulation for the range of diving conditions considered resulted from an exhaustive search of existing and experimental suit materials. An extensive evaluation of commercial wet and dry suits relative to fabrication, range of motion, and thermal protection established a data base from which the formulation of improved thermal protection systems could be derived.[1 2 3 4 5 6] Wet suits were found to give effective and reliable thermal protection to depths of not more than 10 feet (3 metres) during short missions of no longer than 3 hours in 40°F (4.4°C) water. However, wet suits lose their insulating qualities as depth is increased due to compression of the uncrushed neoprene foam. At 33 feet (10 metres) nearly half of the wet suit insulation is lost, and at 100 feet (30 metres) the wet suit offers little thermal protection to the diver (Figure 1).

Dry suits offer a substantial improvement in thermal protection to the diver, particularly when the suit is inflated with air since the insulating effectiveness of any garment is primarily dependent upon its ability to entrap air. Dry suits offer the additional benefit of allowing thermal undergarments to be worn which further improves the diver's warmth. However, as with wet suits, dry suits constructed of uncrushed foam neoprene have less insulation as depth increases. A typical 1/4-inch foam neoprene dry suit with a 0.3-inch (nominal) open-cell foam undergarment will lose approximately 50 percent of its insulation effectiveness as the depth increases to 100 feet (30 metres).[6] Excess thicknesses of insulation (thick undergarments) have to be worn to obtain sufficient insulation for missions at increased depths resulting in bulky, overly warm garments at shallow depths.

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[1]NAVCLOTEXTRSCHF Letter Report, "Inspection of Commercial Dry-Type Divers' Suits," for Work Request N61331-76-WR-T-0002 of November 1976, UNCLASSIFIED.

[2]Naval Coastal Systems Center Technical Memorandum TM 234-78, "Comparative Mobility in Various Dry Suits," Contract with UCLA N61331-76-M-4166, August 1978, UNCLASSIFIED.

[3]Naval Coastal Systems Center Technical Memorandum TM 241-78, "Human Engineering Evaluation of Dry Suits for Navy Use," by F. Wattenbarger and J. Brady, October 1978, UNCLASSIFIED.

[4]Naval Coastal Systems Center Technical Memorandum TM 219-77, "A Subjective Evaluation of Commercial Dry Suits," by F. Wattenbarger, September 1977, UNCLASSIFIED.

[5]Nuckols, M. L., "Thermal Considerations in the Design of Diver's Suits," American Society of Mechanical Engineers Publication DED-Volume 6, pp 83-99, 1978, UNCLASSIFIED.

[6]Wattenbarger, J. F and Breckenridge, J. R., "Dry Suit Insulation Characteristics Under Hyperbaric Conditions," American Society of Mechanical Engineers Publication OED-Volume 6, pp. 101-116, 1978, UNCLASSIFIED.

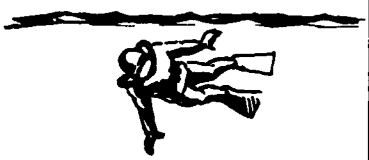
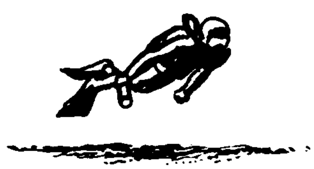
	1/4-inch Wet suit	1/4-inch Foam dry suit with foam undergarment	Coated-fabric dry suit with thermal undergarment
In air 	1.8 CLO	2.5 CLO	2.5 CLO
Surface 	0.75 CLO	1.2 CLO	1.2 CLO
100 FSW 	0.25 CLO	0.75 CLO	1.2 CLO

FIGURE 1. INSULATION OF DIVER'S SUIT

On the other hand, dry suits constructed of thin, rubber-coated fabrics were found to offer nearly uniform insulation qualities at any depth provided the suit inflation gas remained the same. Although the thin dry suit offers little insulation by itself, when used in conjunction with a good thermal undergarment a diver could have nearly uniform thermal comfort as he descends and later surfaces. Such a garment was found to have the additional advantage of minimizing the suit buoyancy changes that occur with foam dry suits as depth is increased. These benefits contributed to the establishment of a design for a thermal protection system which used the coated-fabric dry suit as its foundation. The dry suit outer garment is designed to act only as a flexible water barrier with minimal insulation qualities. The critical component from which this system derives its thermal protection qualities is the thermal undergarment.

PASSIVE DTP SYSTEM DESCRIPTION

The passive DTP system consists of an outer garment which is basically a variable volume dry diving suit with neck and wrists seals. Inlet and exhaust valves are provided to control suit inflation level. Thermal insulation is provided by insulating underwear worn over a cotton "long john" comfort layer and wool socks. Ancillary equipment including dry gloves and a weight distribution system complete the system features. These system components are described.

1. Outer Garment. Based on the previous findings, it was decided to avoid the use of uncrushed closed-cell neoprene foam for the outer garment although most commercial dry suits are fabricated from this material. The good points of both have been taken advantage of in fabrication of the suit by using uncrushed foam in the hood and seals and crushed foam in the body of the suit. The suit consists of a 1/8-inch neoprene foam hood with face seal, a 3/16-inch foam neck seal that is folded up and down against the neck when donned so that increasing internal suit pressure tightens the seal against the neck. The wrist seals are tapered 1/4-inch foam. The body of the suit is 1/16-inch crushed foam with an across-the-shoulder water-sealing zipper entry. The suit is designed to fit closely over the underwear in crotch and seat area to facilitate swimming and reduce excess buoyancy. An exhaust valve is mounted high on the outside of the left arm. The inlet valve is mounted on the left chest. A tab of nylon webbing with a grommet is attached at the left waist to secure the pouch containing the suit inflation cylinder when a closed-circuit breathing system is used. Wrap-around calf and thigh restraints control buoyancy in the leg area. A loop at the ankle retains the ankle weight. A strap from the heel area over the top of the foot restrains inflation and prevents losing swim fins when in a head-down position. A soft sole is attached to the suit boot area. A view of the outer garment design is shown in Figure 2.

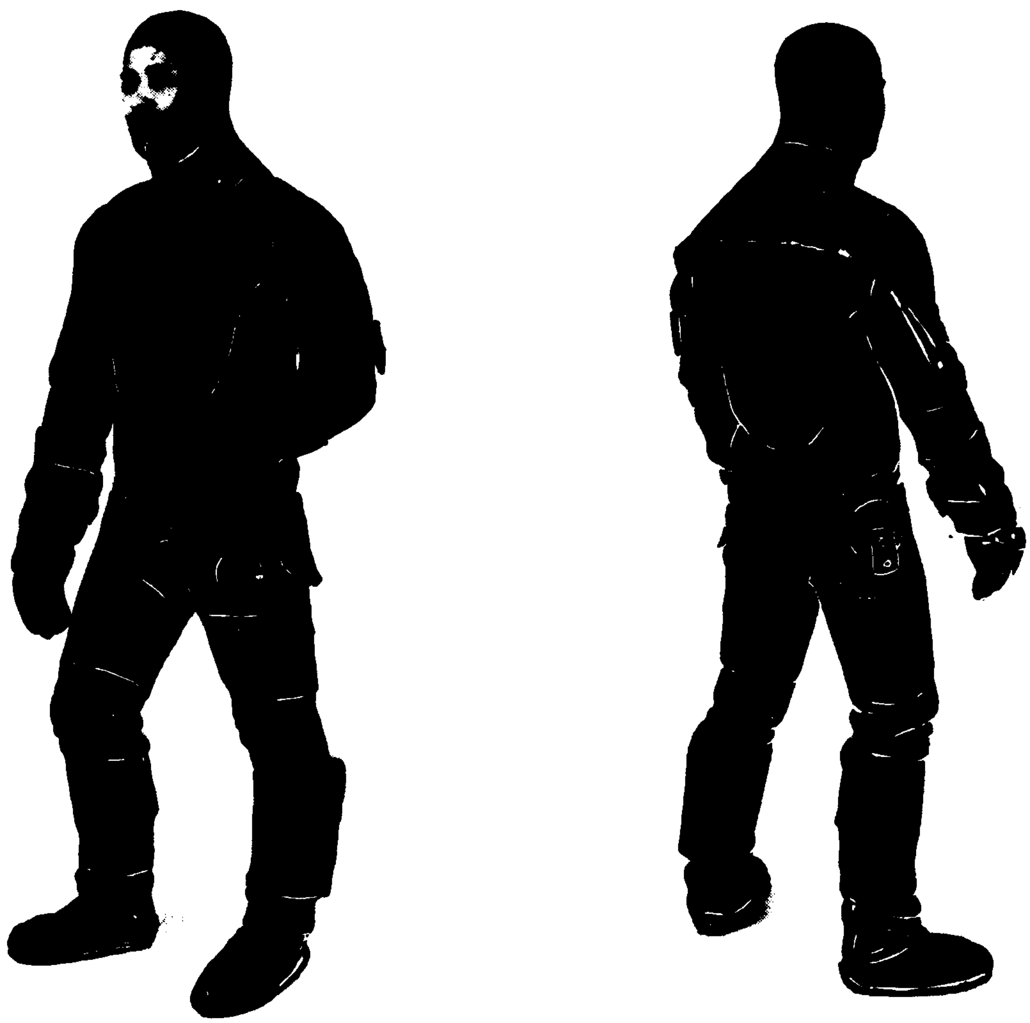


FIGURE 2. PASSIVE DTP SYSTEM INCLUDING OUTER GARMENT

b. Thermal Undergarment. A joint effort led by NCSC, with the Navy Clothing and Textile Research Facility (NCTRF), and with the Navy Experimental Diving Unit (NEDU) participating, has resulted in the development of an improved thermal undergarment for dry suit use. This undergarment (Figure 3) is constructed from a three-part laminate consisting of a neoprene-coated nylon taffeta inner liner, a fine-fiber insulation medium, and a nylon taffeta outer layer. The inner layer acts as a water and vapor barrier to prevent the infiltration of the diver's perspiration into the insulating medium. In so doing, it minimizes the loss of the heat of vaporization (1000 Btu's per pound of sweat) that accompanies the evaporation of perspiration from the diver's body and prevents the degradation of the suit's insulating qualities through wetness.

FIGURE 3. DIVER DRESSED IN THERMAL UNDERGARMENT

The insulation medium consists of a 0.3-inch nominal thickness fine-fiber batt manufactured by 3-M Corporation under the designation of M-400 Thinsulate. This material offers outstanding insulation qualities when dry and, due to its hydrophobic behavior, retains the majority of its insulation qualities when wet.

The outer layer of nylon taffeta provides a smooth surface to facilitate donning the dry suit outer garment over the thermal undergarment. Donning the suit is further aided by the presence of wrist and ankle stirrups to prevent the sleeves and legs from riding up inside the outer garment.

The thermal undergarment is constructed in a coverall arrangement, with separate thermal boots having a double layer of insulation around the foot. The coverall can be separated at the waist into separate pants and jacket to allow the diver to select components which best fit his body shape. Once a satisfactory pants and jacket combination have been selected by the diver, they are snap attached at the waist for permanent functioning as a coverall. Range-of-motion testing has demonstrated that the underwear affords an average of 95 percent of nude mobility for the eight abduction-extension diver movements selected.

c. Weight Distribution System. Since the thermal protection in the passive DTP system is provided by the insulating underwear which derives its insulation value from the gas trapped in the fabric, a significant amount of buoyancy is unavoidable if the necessary amount of thermal resistance is to be provided. One of the most difficult practical problems in the design of the system has been to minimize the excess suit volume that is filled with bubbles of gas which greatly increase the buoyancy, add little extra insulation, and move about as the diver changes his position in the water. These wandering bubbles are particularly annoying in the foot and leg portions but are well controlled by the thigh, calf, and ankle restraints provided on the outer garment. The elastic properties of the crushed foam outer garment material also are an important factor in controlling this excess volume. It is evident that the amount of added weight necessary to produce neutral buoyancy should be kept to a minimum and distributed in such a manner as to keep the diver's center of gravity close to its normal position.

A standard weight belt containing 16 to 20 pounds of weight and a choice of bar and rod weights in pockets on each calf are used with the passive DTP system. For dives where maximum thermal protection is desired, the addition of 3 to 4 pounds of additional weight permits a greater degree of suit inflation and provides an increase in insulation.

d. Gloves. A moderate degree of manual dexterity is usually necessary if the diver is to accomplish his underwater tasks and manipulate his life support system in a safe manner. The majority of the existing diving gloves are fabricated from closed-cell neoprene foam and, when thick enough to afford even a minimum amount of thermal protection, provide very little manual dexterity. Analysis indicated that the best

thermal insulation was provided by a dry glove worn over an insulating liner. The Navy Clothing and Textile Research Facility (NCTRF) is developing a glove of fabric-reinforced, dipped neoprene for use in extreme cold weather in an air environment. This glove was evaluated and found to provide good thermal protection and surprisingly good dexterity. A special insulating liner of C-300 Thinsulate between layers of nylon tricot was developed for maximum insulation when wet with little loss in dexterity.

The equipment necessary to administer five standard tests of manual dexterity underwater was developed and has been used to obtain objective information on glove performance. Since the dry glove selected was not designed for use underwater, a seal between the glove and the suit sleeve was required. Many different sealing methods have been tested and only recently has an acceptable seal using a double O-ring configuration on the wrist ring and a neoprene foam gauntlet covered with Lycra Spandex been developed. In addition to providing a secure, watertight connection with the dry suit sleeve, the glove must be capable of being donned by a diver with no assistance.

As the diver descends, the gas in the dry glove is compressed and a loss of thermal protection and dexterity takes place unless gas is added to the glove. This is accomplished by raising the hand and flexing the wrist so that small quantities of gas leak from the wrist seal into the glove. When the diver ascends, the gas will not pass back through the wrist seal and must be vented to prevent loss of dexterity and glove seal failure. A small exhaust valve is mounted on the back of each glove for this purpose. This valve also is necessary to relieve the pressure when the diver jumps or parachutes into the water.

SYSTEM DEVELOPMENT

The two major components of the DTP passive system, the outer garment and the thermal undergarment, have gone through several iterations of improvements and modifications followed by engineering evaluations. The development of these two components followed unique paths, with the outer garment development primarily constrained by human engineering considerations (comfort, swimability, buoyancy control, etc.) while the thermal undergarment development was driven by considerations in maximizing thermal insulation. A brief summary of these developments follows.

1. Outer Garment. To select the optimum material for the DTP passive system outer garment, a series of tests was conducted to evaluate the tensile strength, abrasion resistance, tear propagation, etc., of various candidate materials. Several suits fabricated of these materials were procured for evaluation. As the testing progressed, it became apparent that materials with a moderate stretch capability permitted much better fit and comfort over the range of diver sizes. This is particularly important because it was planned to stock only four standard sizes of the suit.

The result of the evaluation process was the selection of a material composed of neoprene foam which had been irreversibly crushed to permanently eliminate all closed cells. This commercially developed crushed foam is laminated between layers of nylon knit fabric and appears to be superior in stretch modulus, abrasion resistance, and tear resistance to the other materials considered. In addition, diver evaluators report that crushed foam suits are more comfortable and permit a greater range of motion than suits fabricated from coated fabrics. The suit configuration selected is the result of various features being tested and refined during many dive evaluations. Although the crushed foam was selected for the body of the suit, the material was found to take an excessive permanent set when stretched to 100 percent elongation. This was evident in the neck seal and wrist seal portions which are stretched the most. After the suit had been used a few times, the seals became too loose to prevent water entry or to retain inflation gas. The hood with its face seal also became a problem. On the other hand, uncrushed neoprene foam retains its shape and stretch properties quite well.

To make maximum use of the favorable properties of these two materials, the suit was modified to include both neoprene foam and crushed foam. The hood is fabricated of 1/8-inch neoprene foam with face seals and a 3/16-inch foam neck seal which is folded up and then down against the neck when donned so that increasing internal suit pressure tightens the seal against the neck. The wrist seals are tapered 1/4-inch foam. The body of the suit is of 1/16-inch crushed foam with an across-the-shoulder water-sealing zipper entry.

b. Thermal Undergarment. Conventional undergarments used with existing dry suits are constructed primarily of open-cell foam materials or nylon pile. These materials offer good insulation qualities when dry and uncompressed but lose many of their insulation qualities when wet or compressed. Conventional dry suit systems are difficult to keep completely dry. In addition, the differential hydrostatic pressure which exists in dry suits, i.e., top to bottom or up to down, (causing suit "squeeze") (Figure 4) has a tendency to compress the undergarment materials in the lower extremities. In a vertical position, a diver can experience a 2-psi squeeze in the lower legs and feet.

The effect of this squeeze on a diver's undergarment thickness is seen in Figure 5. This illustrates that most of the material compression occurs within 1 psi differential pressure with up to 80 percent compression by the time the pressure reaches 2 psi for conventional undergarment materials. The effect of this compression on the insulating properties was determined using a guarded hot plate apparatus test procedure[7] and is shown in Figure 6. Note that up to 75 percent of the undergarment's

[7]ASTM-C-177, "Test for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate," American Society for Testing and Materials, UNCLASSIFIED.

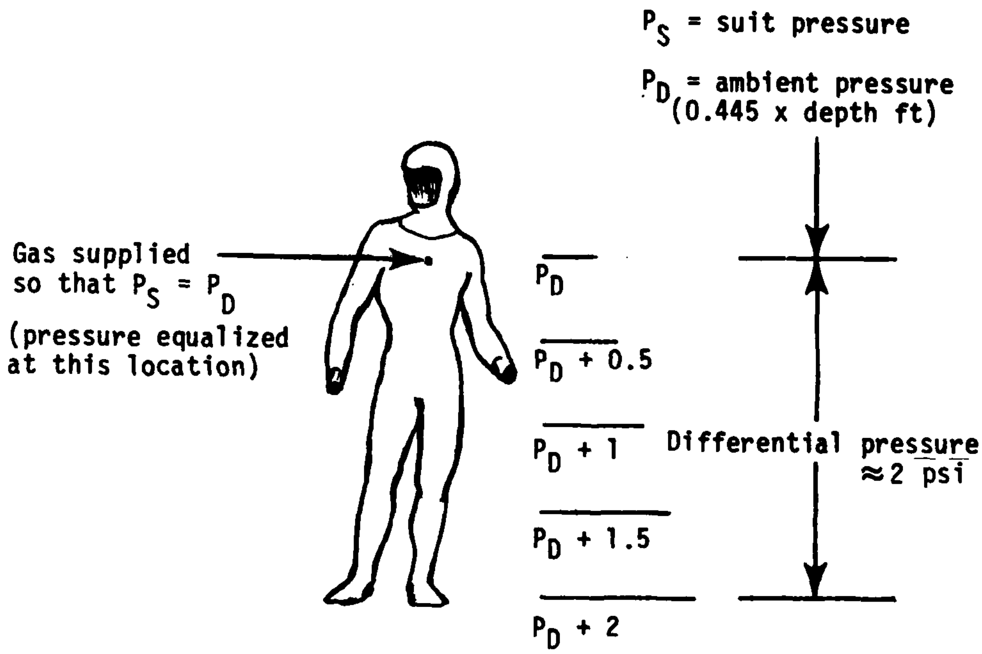


FIGURE 4. COMPRESSION OF UNDERGARMENT DUE TO DIFFERENTIAL PRESSURE AND PRESSURE DUE TO OUTER GARMENT TIGHTNESS

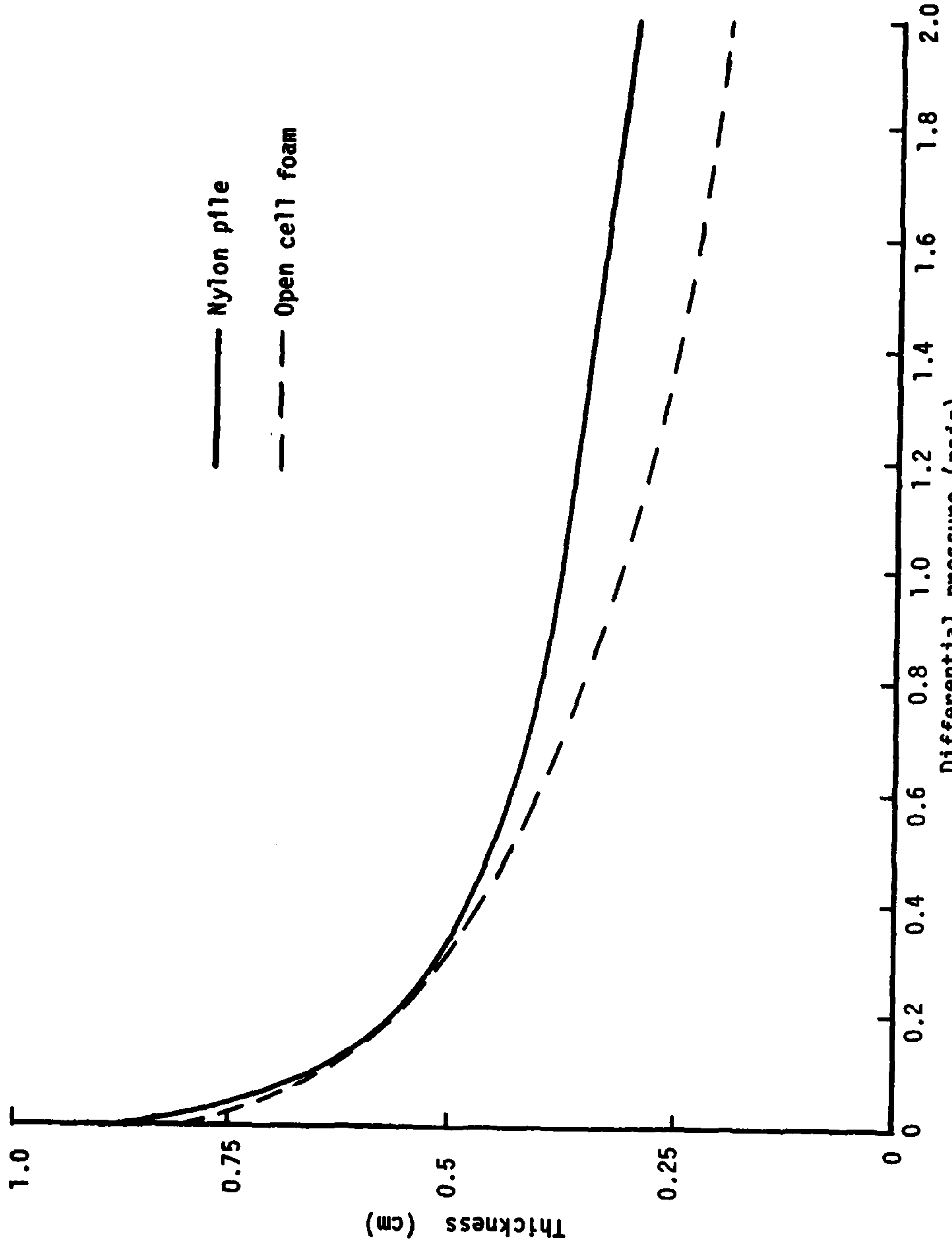


FIGURE 5. THICKNESS OF DIVER'S UNDERGARMENTS VERSUS DIFFERENTIAL HYDROSTATIC PRESSURES

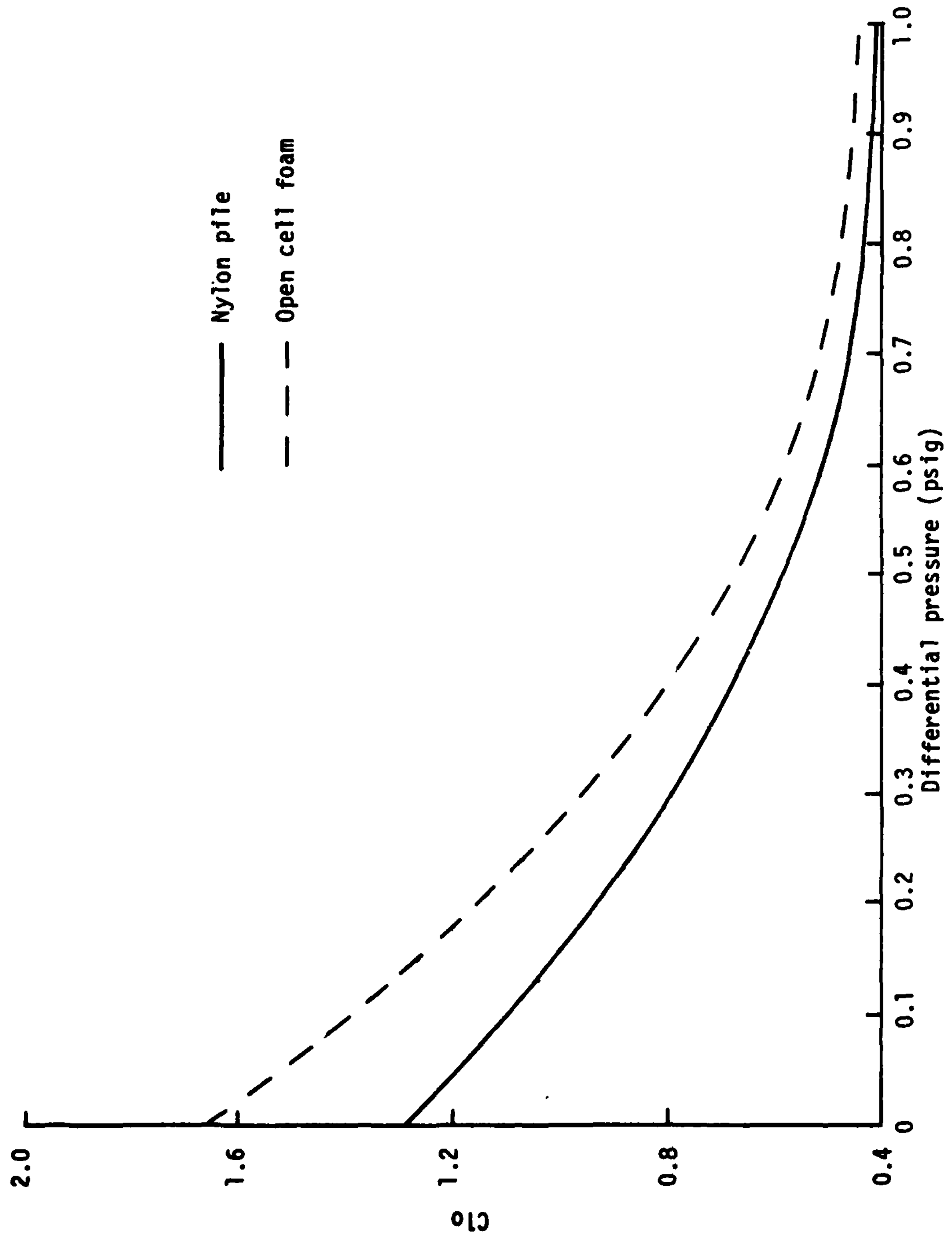


FIGURE 6. INSULATION VALUE OF DIVER'S UNDERGARMENTS VERSUS DIFFERENTIAL HYDROSTATIC PRESSURES

effective insulation has been lost by the time the differential pressure reaches I psi. This reduction occurs mainly in the diver's lower extremities which are difficult areas to keep warm, even with excess insulation. The loss of insulation due to squeeze further compounds the problem of heat loss in the extremities.

Characteristics of Potential Insulation Materials

The insulating deficiencies found in the test of conventional undergarment materials compelled the evaluation of other materials, existing and experimental, for use in thermal undergarments for divers. In FY 1978, NCTRF conducted tests to define specific characteristics of potential insulating materials. Considerations included:

1. Compression resistance to pressures up to 2 psig.
2. Material insulation values that would permit construction of 1.0 to 1.5 clo garments.
3. Resistance to loss of insulation when wet.
4. Diver comfort and mobility.
5. Wear properties in the intended use environment.

Commercially available foam and fibrous insulating materials were investigated with particular emphasis on foam pore size, density, and thickness. The results of this investigation are reported in Reference 8. In general, the major findings were:

1. When open-cell foam materials with compressional resistance to hydrostatic pressures of up to 2 psi are required, they should have a density of 0.12 gram/cm^3 or more. These materials will then have a thickness reduction of less than 30 percent.

2. When foam material with maximum insulation resistance is required, a material with very fine pores should be used. This minimizes heat transfer due to convection within the pores.

3. The maximum density should be no more than 0.12 gram/cm^3 for open-cell foam materials flexible enough for clothing applications.

4. A fine-pore open-cell foam at a density of 0.12 gram/cm^3 will meet minimum thermal insulation requirements (1 clo) at 2 psi when it has an initial uncompressed thickness of 0.79 cm or more.

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[8]Audet, N. F., Orner, G. M., and Kupferman, Z., "Thermal Insulation Materials for Diver's Undergarment," American Society of Mechanical Engineers Publication OED-Volume 6, pp. 133-149, 1978, UNCLASSIFIED.

5. A polypropylene microfiber batt material (designated M-400 Thinsulate) with a high specific thermal resistance at 2 psi of 2.1 clo/cm will meet the 1.0-clo requirement when it has an initial uncompressed thickness of 1.18 centimetres or more even though it undergoes 60-percent compression at 2 psi.

6. High density foams and fibrous batt materials were found superior to all materials presently in use because of better compressional resistance at pressures to 2.0 psi and equal or superior in specific thermal insulation resistance when uncompressed.

The results of this investigation were used to select two candidate insulation materials to construct prototype diver undergarments having nominal uncompressed insulation values of 1.0 and 1.5 clo:

1. A 0.128 gram/cm^3, 90 pore-per-inch (ppi), open-cell urethane foam 0.47 and 0.79 centimetre thick (designated SI-90-8).

2. A 0.057 gram/cm^3 fibrous, polypropylene batt material 0.82 and 1.63 centimetres thick (M-400 Thinsulate).

The specific thermal insulation values of these two materials and their thickness changes due to compression are compared with conventional undergarment materials in Figures 7 and 8.

Both materials showed significant improvements over conventional materials in either insulation properties (Figure 7) or thickness changes due to suit squeeze. Each had a clear advantage over the other in one of these areas. Both materials were found to give the minimum insulation requirement (1.0 clo) when dry, even when subjected to the compressional forces due to suit squeeze. However, when wet, the M-400 Thinsulate showed a clear advantage in insulation retention as demonstrated in Table 1 and schematically in Figure 9.

TABLE 1

THERMAL PROPERTIES OF CANDIDATE AND IN-USE MATERIALS IN DIVER'S GARMENTS

Material	Thermal Conductivity (K) Btu/ft-hr-°F		Thermal Resistance (clo/in.)	
	Dry	Wet	Dry	Wet
Foam neoprene (wet suit material (in-use)	0.030	0.030	3.16	3.16
Open-cell urethane foam	0.021	0.121	4.51	0.78
M-400 Thinsulate	0.019	0.027	4.98	3.51

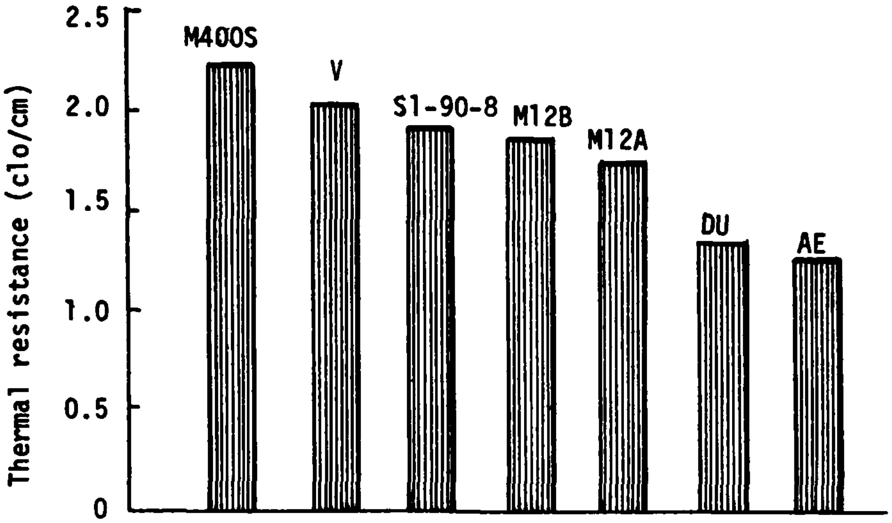

FIGURE 7. COMPARISON OF THE SPECIFIC THERMAL RESISTANCES OF CANDIDATE INSULATION MATERIALS

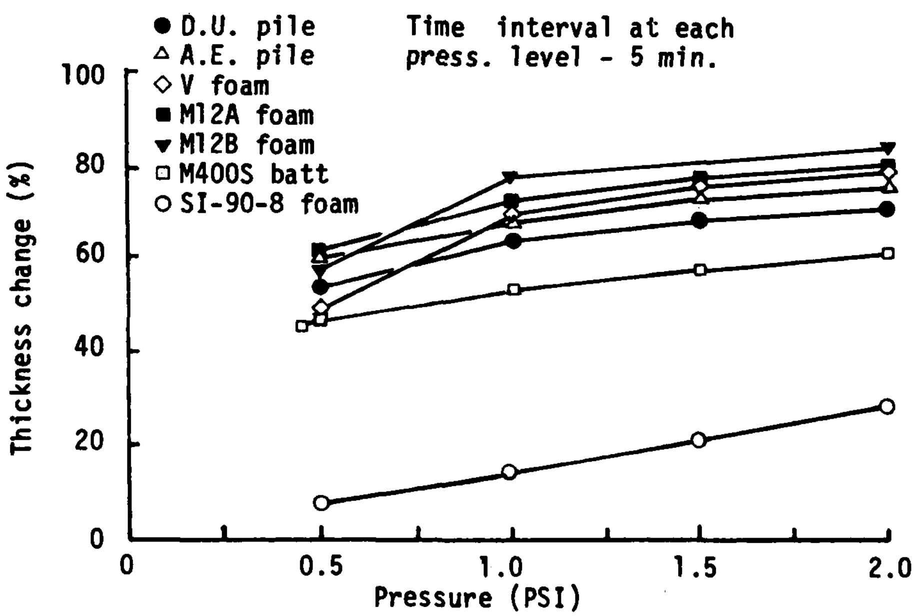

FIGURE 8. THICKNESS VERSUS PRESSURE FOR VARIOUS FIBROUS BATT AND FOAM MATERIALS

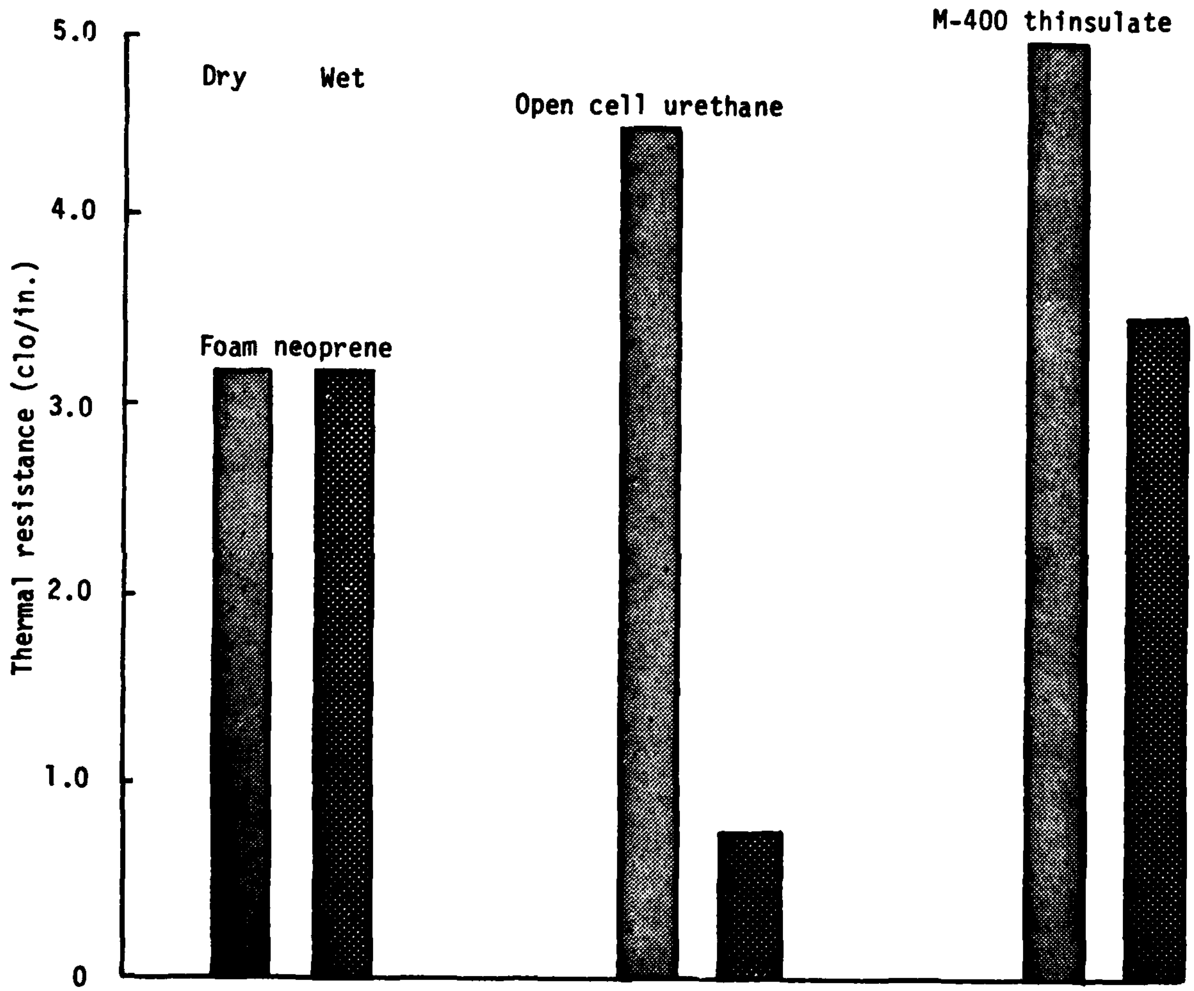

FIGURE 9. COMPARISON OF SPECIFIC THERMAL RESISTANCE OF DIVER GARMENTS BEFORE AND AFTER SUIT FLOODING

The M-400 Thinsulate had a weight increase of approximately 17 percent due to water absorption after being submerged in water for 6 hours. This resulted in an increase in thermal conductivity of approximately 42 percent; still the insulation was better than foam neoprene. By contrast, the urethane foam (presently used in garments) showed a weight increase of approximately 750 percent with a corresponding increase in thermal conductivity of 476 percent. From these data it is clear that the M-400 Thinsulate is a better material for use in diver's undergarments if suit wetness is a concern, a common situation with conventional dry suits. In addition, the Thinsulate was more supple and more comfortable than the foam when fabricated into a garment.

Testing in addition to that shown in Table 1 indicates that more water absorption can occur for M-400 Thinsulate under elevated hydrostatic pressure and through wringing action. However, the M400 Thinsulate showed the highest resistance to water absorption of all open-cell materials tested.

PASSIVE SYSTEM THERMAL EVALUATION

The overall effectiveness of the passive thermal system could not be appraised until thermal evaluations with divers had been conducted. Two dive series were conducted by the Navy Experimental Diving Unit during FY 1979 and FY 1980 to evaluate its thermal characteristics. The first series of 2-hour dives in 37.9 to 42°F (3.3 to 5.6°C) water temperatures found the DTP passive system adequate over a range of metabolic levels.[9] The second series of 6-hour dives in 39.7 to 42°F (4.3 to 5.6°C) water temperatures found this system to be satisfactory to maintain a diver well within established thermal physiological criteria[10] for 6-hour missions, even at resting metabolic levels. A complete description of this test series and results can be found in Reference 11.

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[9]US Navy, Navy Experimental Diving Unit Report 13-79, "Manned Evaluation of the NCSC Diver Thermal Protection (DTP) Passive System Prototype," by C. A. Piantadosi, D. J. Ball, M. L. Nuckols, and E. D. Thalmann, August 1979, UNCLASSIFIED.

[10]Physiological Design Goals for Thermal Protection of Divers," prepared for the Naval Medical Research and Development Command by Webb Associates, Yellow Springs, Ohio, September 1980, UNCLASSIFIED.

[11]US Navy, Navy Experimental Diving Unit Teport 10-81, "Manned Evaluation of an Improved Passive Diver Thermal Protection System," by J. L. Zumrick, (in publication) UNCLASSIFIED.

DISCUSSION

The development of the DTP passive system has made an improvement to the thermal protection that Navy divers can expect in cold water operations. The range of motion demonstrated during its development will allow the diver to complete his mission with minimum restrictions. Additionally, and perhaps most important, the DTP passive system has been shown to interface well with many of the Navy's existing breathing gas systems (scuba, MK 15, MK 1 lightweight) and to be adaptable to other systems with minimal modifications.

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